DETERMINATION OF THE THERMAL BOUNDARY CONDITIONS DURING ALUMINUM DC CASTING FROM EXPERIMENTAL DATA USING INVERSE MODELING

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Abstract

Thermal boundary conditions applicable to the stationary part of DC casting have been determined using a laboratory set-up and 2D inverse modeling techniques. The influence of (non casting) parameters on the accuracy of the results is clarified, and the influence of casting related parameters, such as casting speed, water flow rate, temperature, surface structure and type of waterfilm generator on the thermal boundary condition has been examined. This investigation shows that the classical description of a heat transfer coefficient or heat flux as a function of surface temperature alone does not accurately describe the thermal boundary condition typical for DC casting. To account for the effect of impingement and re-heating of the surface in the downstream area, the heat flux as a function of the distance from the impingement point should also be considered. The results show that the effect of the casting speed is mainly expressed in the pre-impingement and impingement zone, whereas the effect of cooling water flow rate is principally expressed in the downstream area.

Introduction

The work described in this contribution is part of the Brite-Euram project EMPACT. In this project several European partners (both from industry and university) have joined to develop tools for improving the casting of aluminum ingots. It focuses on the development of mathematical models which describe the micro and macro segregation, the fluid flow and the thermo-mechanical behavior of the DC cast ingots. An accurate description of the thermal boundary conditions is of paramount importance for the correct simulation of the casting process. Moreover, these boundary conditions serve also as control parameters in practice. Nowadays inverse modeling techniques can be used to infer the thermal boundary conditions from thermocouple measurements during actual casts. Although this is the best way to obtain thermal boundary conditions for actual casting conditions, it is rather impractical when the influence of a large number of (casting) parameters is to be established over a broad range. In the present study the influence of several practical parameters on the thermal boundary conditions has been determined experimentally in the laboratory.

Method of determination of the thermal boundary conditions

Experimental set-up

The set-up, of which a sketch is shown in Figure 1, consists of a large aluminum block (height x width x thickness = 1 x 0.25 x 0.13 m^3). Except for the measuring surface (the cooled surface) all sides of the block are thermally insulated. Cooling is realized by means of a waterfilm which ascends at a constant speed to simulate the steady-state situation of secondary cooling in the actual DC casting process. Inside the block two arrays of four thermocouples (hereafter referred to as TC) each are mounted.

Operating procedure

The block is electrically heated to the starting temperature T_{start}. When the desired temperature is reached the temperature is allowed to homogenize. Then the device generating the waterfilm is positioned at a predetermined height and distance from the measuring surface. Subsequently the water supply is switched on (at the predetermined flow rate, Q_{water}, and temperature of the water, T_{water}), the device generating the waterfilm is set in motion at the desired ascending speed, v, and data logging is started.

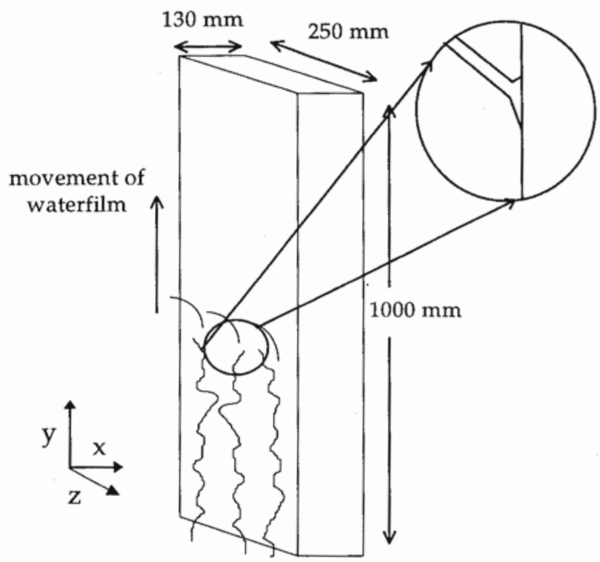

Figure 1. Sketch of the experimental set-up.

Data processing

Since the cooling conditions can be considered stationary, the time histories of the recorded temperatures may be converted into temperatures as a function of the distance from the impingement point. Thus a 2-D temperature field of the stationary cooling regime is obtained from the logged data. Using the technique of inverse modeling the heat flux (q) at the surface responsible for this 2-D temperature field (e.g. see Rappaz et al. [1]) can be obtained. The FEM code calc●*MOS*™ is used to this end. The inverse modeling routine which was employed here basically consists of three steps:

1. Calculation of the temperature field inside the block with an estimated q(y) relation as input, in which y is the vertical distance to the impingement point of the waterfilm cooling zone,
2. comparison of the measured temperatures with the calculated temperatures at corresponding locations,
3. Adjustment of the q(y) relation.

This cycle is repeated until the (sum of the squared) differences found in step 2 are minimized to an acceptable level. By combining the resulting q(y) relation and the temperature profile at the surface (T_{surf}) along the height of the block, the q(T_{surf}) relation can be obtained.

Sensitivity of the boundary conditions to the method of determination

There are several parameters in the process of determining the boundary conditions searched for which might influence (the accuracy of) the result, although they are not related to the actual boundary conditions. The influence of these (non-casting) parameters was examined in great detail and the findings are summarized below:

1. Type of function searched for: the inverse modeling routine seeks a boundary condition which results in the best correspondence between calculated and measured temperatures in the block. The type of function searched for can be either a temperature imposed, heat flux function or a heat transfer coefficient function. For several reasons it is rather impractical or in some cases even impossible to search for the heat transfer coefficient as a function of surface temperature directly by applying the inverse modeling procedure:

- If the heat transfer coefficient is to be known, the water temperature is to be known in the impingement zone, as well as downstream from this zone, where the water temperature is no longer constant due to heat absorbed from the block. Since this is not the case it seems more straightforward to seek for heat flux values rather than heat transfer coefficient values.
- If re-heating occurs, and consequently different values of the heat flux (or heat transfer coefficient) at the surface occur at the same surface temperature (but in different zones of the waterfilm cooling), it is physically unrealistic to try to obtain the heat flux (or heat transfer coefficient) as an unambiguous function of the surface temperature.
- Due to the fact that the surface temperature depends on the heat extracted from the block (the heat flux), it is very impractical to search for the heat flux as a function of surface temperature (even in cases where no re-heating occurs). In fact, the routine then seeks for a function which depends on part of the result of the calculation in stead of a constant (such as the vertical position along the block). This results in oscillations in the calculated temperatures which can only be suppressed by taking a very large number of very small time steps resulting in a very time-consuming routine. In some cases the routine even did not converge at all.

For the above reasons the heat flux as a function of the distance from the impingement point was searched for: a q(y) function. From this function and the calculated temperature profile at the surface, the q(T_{surf}) function can readily be obtained, and if desired the h(T_{surf}) relation as well.

2. Location of impingement point: to determine the heat flux as a function of the distance from the impingement point, the location of the impingement point has to be known. This point was determined from the data, by determining the maximum temperature drop in the measured temperature-time profile (dT/dt_{max}) of the TC closest (3 mm) to the surface. At this time the cooling by impinging water starts and thus the location is obtained. Due to the limited thermal conductivity an error in the order of 1 mm results .

3. Proximity of TCs to the cooled surface: measurements obtained for the same cooling conditions (water throughput, water temperature, etc.) but with different TC locations showed that when the distance of the first TC is too large (TC1 in Figure 2a is at x = 6.5 mm) oscillations in the predicted surface temperature result. Due to the limited heat conduction such oscillations may result since their effect deeper in the block (at the TC locations) is dampened. When the distance to the first TC is decreased (TC1 in Figure 2b is at x = 3 mm) such oscillations no longer occur.

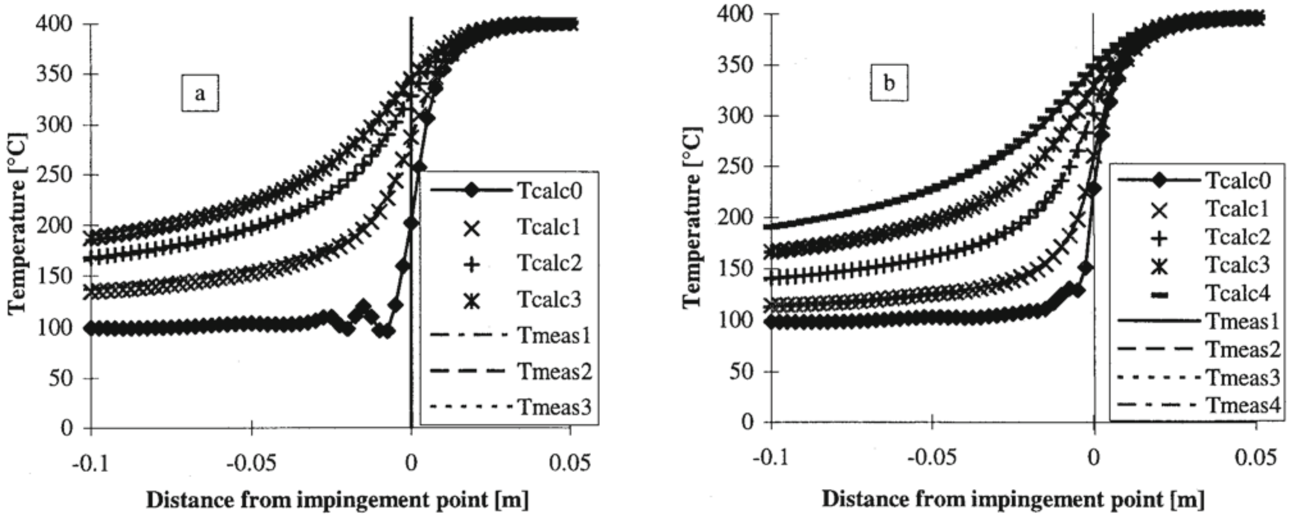

Figure 2. Influence of proximity of TCs on temperature at the surface for TC1 at x = 0.0065 m (a) and TC1 at x = 0.003 m (b).

4. Discretisation and selection of reference locations: the inverse modeling routine optimizes the function searched for (here the q(y) relation) by adjusting the q values at a discrete number of y-locations: the reference locations. The selection of the specific reference locations has a significant influence on the result obtained from the inverse modeling routine. Because of this and because of the limited accuracy in the determination of the impingement point from the experimental data, several sets of reference locations (where the heat flux is estimated) were used. From the various sets of reference locations investigated it could be concluded that the influence on the heat flux can be rather substantial, although only in the impingement zone and adjacently upstream. The final choice was based on the value of the residue (measure of the difference between the measured and calculated temperatures inside the block) and the reliability (stability against different initial values and different sets of measured data) of the calculated results.

5. The surface temperature oscillations discussed before, can also be suppressed by using a coarser discretisation for the dependency of the heat flux on the distance from the impingement point. Such a coarse discretisation is undesirable though, since the impingement zone where the bulk of the temperature drop at the surface occurs is relatively small. By putting a perspex plate in front of the waterfilm device during operation the impingement zone was found to be approximately 10 - 15 mm long. It was deduced both from the experiments and from theoretical considerations based on the thermal penetration depth that, if the first TC is located at 3 mm from the cooled surface, the maximum discretisation which can be used for the searched for q(y) function is approximately 2.5 mm.

6. In the EMPACT program it was envisaged that by investigating also other alloys than AA1050, the effect of surface structure on the $q(T_{surf})$ function could be obtained. To this end additional test blocks made from alloys AA3104 and AA5182 were prepared. Obviously, if the inverse modeling routine is to be accurate, the material properties of these alloys must be known accurately.

The material properties of the alloys were calculated using the program ALSTRUC[1]. from the properties of the alloying elements. The data from measurements in literature [2] however differ from the material properties calculated for AA5182 and AA3104. In particular the thermal conductivity values obtained from [2] are up to 10 % higher than the ALSTRUC values. Therefore the influence of the various material properties on the $q(T_{surf})$ function obtained from the inverse modeling routine described above was investigated. When the experimentally determined material properties [2] are used for the AA5182 alloy in stead of the ALSTRUC values, some 10 % higher heat fluxes result, while no influence on the calculated surface temperature is found.

7. The location of the TCs is not known exactly in these experiments, both in depth (x) as in vertical position (y) in the block. Therefore the influence of shifted TC locations on the $q(T_{surf})$ function obtained from the inverse modeling routine described above was examined. This analysis shows that an inaccuracy of 0.5 mm in the x-location of the TCs causes 5 % difference in the calculated surface temperature everywhere, whereas it leads to significant differences in the calculated heat flux only in the impingement zone; here 5-10 % differences in the heat flux values may result. A 0.5 mm inaccuracy in the vertical direction (y) has less impact on the $q(T_{surf})$ relation.

Comparison with casting trial

Early in the project an attempt was made to obtain an aluminum block with cast-in TCs. Although this block was found to be unsuitable for accurate measurements because the first TC was too far from the surface, it could well be used to validate the laboratory experiments. During the cast the TC signals were recorded. The thermal boundary conditions during the cast were obtained from these measurements by inverse modeling. This

[1] Courtesy of Elkem

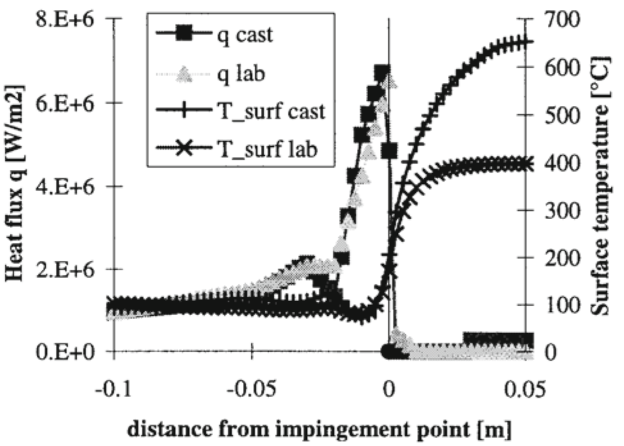

Figure 3. Comparison between casting experiment and typical laboratory experiment.

result is compared with the results from inverse modeling a typical laboratory experiment on the same block in Figure 3.
The casting conditions were: Q_{water} = 100 l/(m min) and v = 1.27 mm/s, whereas the laboratory conditions were: T_{start} = 400 °C, Q_{water} = 120 l/(m min) and v = 6.64 mm/s with a closed waterfilm generator type.

The relatively good agreement merely indicates that the reference parameters used for the laboratory experiments result in similar thermal boundary conditions as is found in the casting practice. It is clear that the heat flux, impingement temperature and length of the impingement zone compare favorably.

Influence of operational parameters

Having established the inaccuracies in the q(T_{surf}) function obtained by applying the inverse modeling routine, next the influence of operational (casting) parameters on the thermal boundary condition is investigated.
In order to facilitate the examination of the influence of the various operational parameters all parametric influences are compared to a reference set of parameters.
The results of the inverse modeling routine for this reference case are shown in Figure 4 and Figure 5. In Figure 4 the heat flux and surface temperature are shown as functions of the distance from the impingement point and in Figure 5 the heat flux is shown as a function of the surface temperature.
In these figures five distinct regions can be observed:

1. the pre-impingement zone, where the surface temperature decreases mainly by vertical conduction (advance cooling), however, some heat extraction at the surface is also predicted,
2. the impingement zone, where a sharp peak in the heat flux occurs,
3. an intermediate zone reaching up to 2 - 2.5 cm downstream of the impingement point,

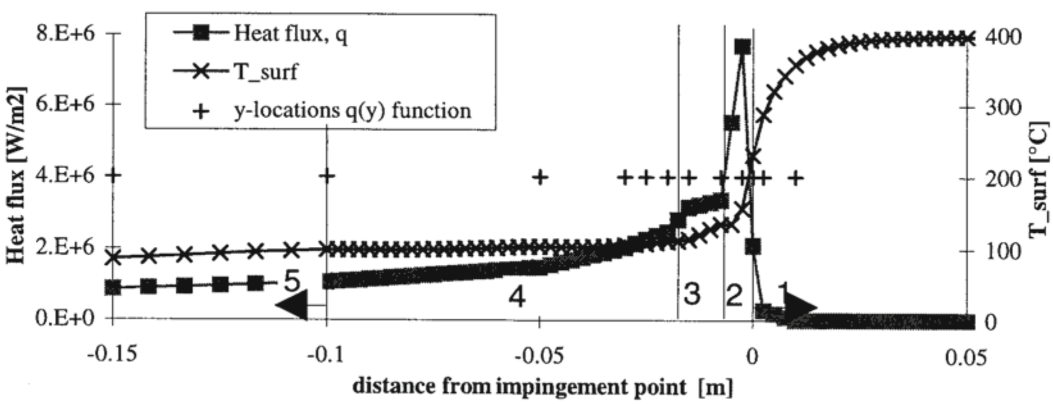

Figure 4. Heat flux and surface temperature as a function of distance from the impingement point as obtained for the reference set of operational parameters.

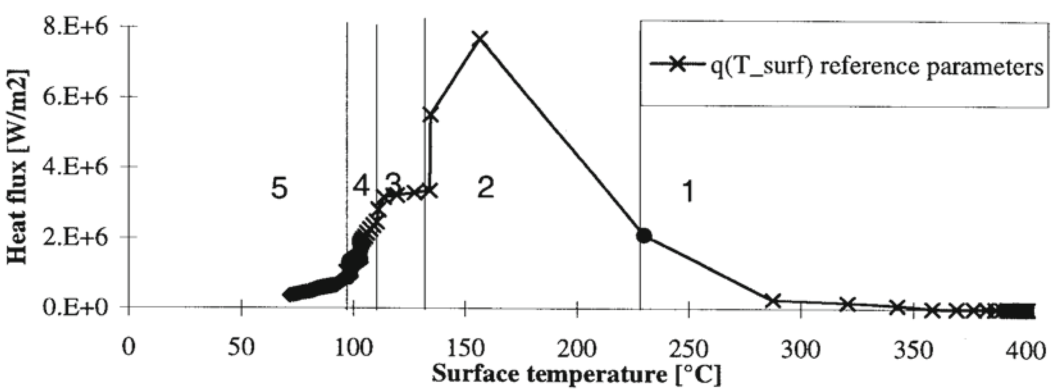

Figure 5. Heat flux as a function of surface temperature as obtained for the reference set of operational parameters.

4. a zone where nucleate boiling occurs. Here the heat flux continuously decreases while the surface temperature approaches 95 - 100 °C,
5. and finally a zone of convective cooling.

The decrease in heat flux in regions 1 and 2 to the right of the peak heat flux value in Figure 5, should not be mistaken for the transition to film boiling in the classical $q(T_{surf})$ relations often found in literature. Here cooling by impinging water simply has not started yet. The black dot in the curve shown in Figure 5 indicates the start of the impingement zone.

Cooling water flow rate

In Figure 6 the influence flow rate of the cooling water on the heat flux as a function of the surface temperature is shown. In the impingement zone no consistent influence of the water quantity can be observed; the highest value is predicted for 240 l/(m min). In the downstream zone a higher heat flux is observed for larger water amounts, resulting in a correspondingly lower surface temperature.

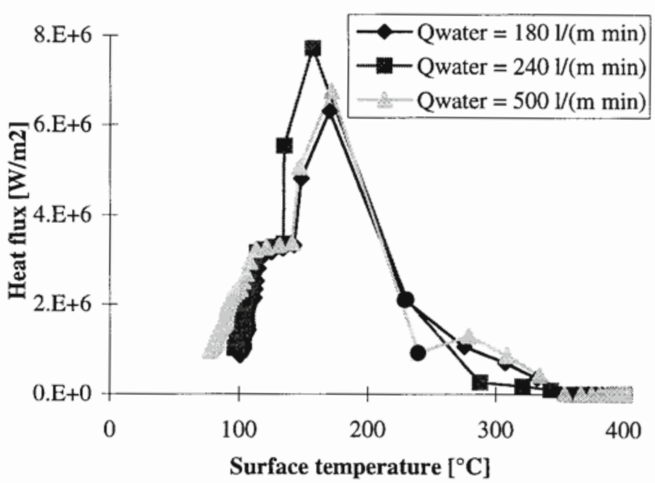

Figure 6. Influence of water amount on $q(T_{surf})$.

Ascending speed (casting speed)

In practice one of the variables is the casting speed. In our laboratory experiments this influence is simulated by changing the ascending speed of the waterfilm device. Consistently higher heat flux values and higher surface temperatures as functions of y are found at higher speeds. This is not so surprising since advance cooling will be less at higher speeds and the cast metal stays shorter in the impingement zone, thus increasing the impingement temperature. The resulting $q(T_{surf})$ functions are shown in Figure 7. The agreement of the $q(T_{surf})$ functions in the down-streaming zones is excellent for all speeds. The only difference is that (more) data on the convective cooling regime result at lower speeds.

The data for v = 1.66 mm/s indicate that the $q(T_{surf})$ function has entered the convective cooling region immediately below the intermediate zone. In [3] a theoretical relation for the $q(T_{surf})$ function is deduced for this regime, depending on the cooling characteristics (water temperature, throughput and fluid properties). The result for this case is also shown in Figure 7. The agreement is excellent.

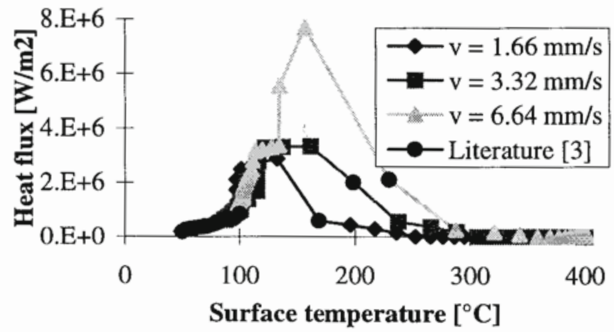

Figure 7. Influence of speed on $Q(T_{surf})$.

Impingement temperature

The amount of heat which can be extracted from the block during an actual cast depends on the melt temperature, the casting speed and the latent heat of solidification. In our laboratory experiments we cannot use the solidification heat because the starting temperature should always remain below the melting temperature. Therefore, the amount of heat which can be extracted in experiments will always be too low if the ascending speed of the waterfilm in the experiment is set to the same value as the casting speed in practice.

The above-mentioned differences were shown to lead to a considerably lower impingement temperature, thereby affecting the entire $q(T_{surf})$ relation (Figure 7). To compensate for this effect the ascending speed of the waterfilm can be increased. In casting practice typically the impingement temperature is in the range of 200 - 300 °C. Using an ascending speed of 6.64 mm /s, a water flow density Q = 240 l m^{-1} min^{-1} and a start temperature T_{start} = 400 °C an impingement temperature of approximately 230 °C was obtained for alloy AA1050 in the laboratory experiments. In casting practice the impingement temperature depends on the metal head in the mold, the casting temperature, the length of the air gap, the casting speed and the material properties of the cast alloy. In our experiments only a few of these parameters can be considered.

Starting temperature

By increasing the starting temperature of the block from 300 °C to 500 °C a correspondingly higher heat flux and higher impingement temperature could be observed. The peak heat flux value in the impingement zone however, does not rise correspondingly with increased starting temperatures. A maximum is observed for T_{start}= 450 °C. This may be caused by the phenomenon that at such high impingement temperatures transition to film boiling occurs.

The $q(T_{surf})$ relation for these cases indicates that the increased heat flux values and temperatures in the down-streaming zone do not affect the $q(T_{surf})$ relation in that region, only the impingement zone shows significant differences.

Ascending speed and water flow rate combined

By a systematic change in both the ascending speed and the water flow rate the impingement temperature and the peak heat flux value were found to be strongly correlated to the ascending speed, not to the water flow rate.

Further, it was found that the $q(T_{surf})$ relation in the downstream zone is insensitive to the ascending speed but is dominated by the water flow rate instead.

Alloy

The differing material properties of different alloys can also lead to different impingement temperatures. This is illustrated in Figure 8 where the result for three alloys with the same(smooth) surface finish is shown. The AA3104 and AA5182 alloys, with their substantially lower thermal conductivity lead to a lower heat flux than the AA1050 alloy. It is clear from the figure that in fact almost the entire $q(T_{surf})$ relation is affected by the type of alloy.

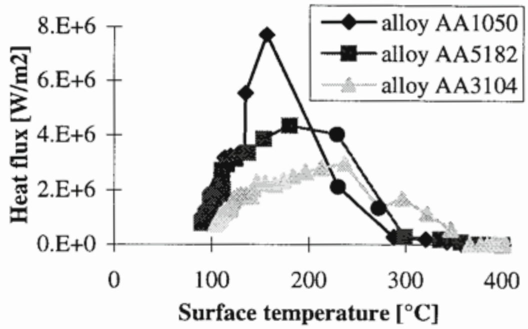

Figure 8. Influence of alloy on $Q(T_{surf})$.

The $T_{surf}(y)$ relations shown in Figure 9 indicate that the heat flux is predominantly influenced in the impingement zone only, but the surface temperature over a larger region. The alloys having a low thermal conductivity show the highest impingement temperature, whereas the maximum heat flux values are lower. This could be an indication of a transition to film boiling at these high impingement temperatures.

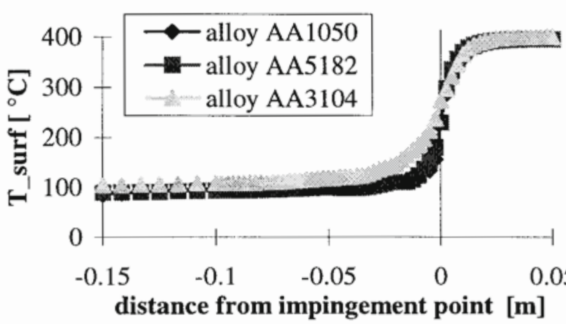

Figure 9. Influence of alloy on $T_{surf}(y)$.

Surface roughness (alloy and surface treatment)

One of the reasons for examining different alloys was that the different material properties could influence the impingement temperature and thus the $q(T_{surf})$ relation. Furthermore, the difference in surface structure generated during casting of the different alloys could also influence the $q(T_{surf})$ relation. The most pronounced influence is found for the different surface treatments of the AA5182 alloy but the effect is small compared to the effects of other parameters considered.

Cooling system (Wagstaff or Duffel type waterfilm)

In the present campaign two different types of waterfilm generators have been used. One (the Wagstaff type) is a closed system where the water leaves the generator through a narrow slit (2.3 mm). The other (Duffel type) is an open system where water flowing from multiple holes forms a waterfilm on the generator surface (the mold interior), from which it flows onto the cooled surface.

The results showed that the closed waterfilm imposes a higher maximum heat flux in the impingement zone (and subsequent lower impingement temperatures), whereas the open waterfilm generator shows higher heat flux values and subsequently lower surface temperatures in the downstream region.

It should be noted that in both measurements with the open waterfilm generator the change in slope, marking the start of convective cooling, could not be distinguished in the results although the surface temperature has decreased to values well below 100 °C. This phenomenon can also be observed in the measurement with a large water quantity, shown in Figure 6.

Water temperature

In general it was found that higher water temperatures result in lower heat fluxes and (somewhat) higher surface temperatures. The effect of water temperature (in the range of 20 - 40 °C) is small compared to the influence of the other operational parameters in steady state cooling.

Comparison with other investigations

Critical heat flux

In Figure 10 the results for the q(Tsurf) relation obtained by several authors are shown. The critical heat flux (CHF) is the peak value in the q(Tsurf) relation. It is clear from this figure that there is a considerable spread in the CHF values found in literature. The values obtained for the AA5182 alloy in our experiments compare favourably to the values given by Bakken and Bergstrøm [4]. The present data for the AA1050 alloy compare favourably with the data given by Jensen et al. [5] and those given by Grandfield et al. [6], both obtained from casting experiments using alloy AA6063.

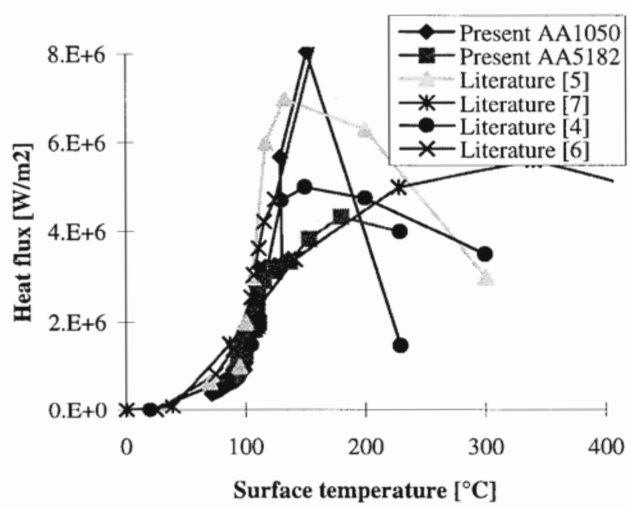

Figure 10. Comparison with literature data.

The values obtained by Yu [7] differ almost over the entire range, showing a CHF of approximately 5.5 MW/m^2 at 350 °C. This may be not so surprising, since these values were obtained from quench experiments, therefore lacking the characteristic impingement and convective cooling features observed in the other studies.

Considering all possible influences of differences in operational conditions on the different results found in literature, the agreement is good. In fact, if all relevant casting parameters would be available the data presented here and in the literature should form a solid framework for a theoretical model of the cooling conditions applicable to the secondary cooling in DC casting.

Convective cooling

The comparison of the present data with the theoretical values obtained for the convective cooling part of the down streaming zone [3] has already been illustrated (Figure 7). It was shown there that the theoretical values and the measurements compare favorably. However, it is not understood why in some cases (e.g. Figure 6 for Q_{water} = 500 l/[m.min]) no transition to convective cooling can be observed while the surface temperature has already dropped below 100 °C.

Conclusions

The conclusions of the work described in this report are divided into conclusions concerning the method applied to obtain the results and conclusions concerning the influence of the operational parameters on the $q(T_{surf})$ relation.

Method

- The influence of operational parameters on the $q(T_{surf})$ relation can successfully be studied under laboratory conditions using the present set-up.
- A 2-D inverse modeling routine as provided by calc ●*MOS*™ is essential to obtain accurate results from the present experimental set-up.
- The specific cooling conditions found in secondary cooling of cast ingots imply that q(y) should be searched for by the inverse modeling routine rather than $q(T_{surf})$. The $q(T_{surf})$ relation can be retrieved by combining q(y) and $T_{surf}(y)$, resulting from the (inverse) model.
- In order to obtain an acceptable resolution in the $q(T_{surf})$ relation, the TCs must be close to the surface. In our studies 3 mm proved to be adequate.
- The results from the 2-D inverse model are influenced by the procedure followed. Although most of these (non-casting) influences have only minor effects, notably the impingement zone is sensitive to some of them.
- Comparison of data from a casting experiment with laboratory data obtained on the same block show that the laboratory results can be considered representative for the casting conditions.

Operational parameters

- Different zones can be distinguished in the cooling curves: 1 Pre-impingement (advance cooling), 2 Impingement, 3 Intermediate, 4 Nucleate boiling and 5 Convective cooling. The heat flux in regions 1, 2 and 3 is mainly related to the position along the block, whereas in regions 4 and 5 it is more related to the surface temperature.
- The influence of water quantity is predominantly felt in the nucleate boiling regime and in the convective cooling regime
- The influence of ascending speed (equivalent to casting speed) and starting temperature is predominantly felt in the pre-impingement and impingement region.
- The $q(T_{surf})$ relations obtained from blocks made from different alloys show significant differences over the entire temperature range.
- The type of waterfilm generator also affects the entire $q(T_{surf})$ relation although not so pronounced as the type of alloy.
- The water temperature (from 20 °C to 40 °C) has only a minor effect on the $q(T_{surf})$ relation during stationary cooling.
- The data obtained in this research compare well with data from literature.

Acknowledgments

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